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Bark-scratching of storm-felled trees preserves biodiversity at lower economic costs compared to debarking

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ABSTRACT

The simultaneous control of insect pests and compliance of conservation targets in conifer-dominated forests has intensified public debate about adequate post-disturbance management, particularly in protected areas. Hence, mechanical bark treatments, such as debarking, of disturbance-affected trees have been widely promoted as an on-site method of pest control that accounts for conservation targets because woody biomass is retained. However, the effects of debarking to non-target biodiversity remain unclear. We analyzed data from a two-and-a-half-year field survey of wood-inhabiting fungi, saproxylic beetles and parasitoid wasps in twelve artificial windthrows, created by pulling down mature Norway spruce trees (*Picea abies*) with winches. Each experimental windthrow comprising one control tree, one completely debarked tree and one bark-scratched tree. Insects were sampled using stem emergence traps. Fruiting bodies of wood-inhabiting fungi, number of wood wasp emergence holes, and number of holes made by foraging woodpeckers were assessed by visual counts. We recorded the amount of time needed to complete debarking by machine, bark-scratching by machine and bark-scratching by chainsaw each on 15 separate trees to estimate the economic costs of mechanical bark treatments.

Our results revealed that both debarking and bark-scratching significantly decreased numbers of the emerging target pest *Ips typographus* to in median 4% (debarked) and 11% (scratched bark) of the number of individuals emerging from untreated control trees. Compared to control trees, debarking significantly reduced the species density of wood-inhabiting fungi, saproxylic beetles, and parasitoid wasps. By contrast, bark-scratching did not reduce the overall species density of wood-inhabiting fungi, saproxylic beetles or parasitoid wasps. The time needed for bark-scratching by machine was significantly lower than debarking, whereas bark-scratching by chainsaw needed a similar amount of time as conventional debarking. However, bark-scratching did have some negative effects in common with debarking, such as the significant reduction of wood wasps emergence holes and the reduction of holes made by foraging woodpeckers. Hence, bark-scratching of downed trees, like debarking, might affect higher trophic levels of biodiversity and should be applied only if pest management is urgently needed. We urge policy makers and natural resource managers to rapidly shift current pest management toward new techniques of bark-scratching, particularly in protected areas. Such a shift in post-disturbance pest-control will foster ecosystem integrity at lower economic cost compared to debarking.

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1. Introduction

Coniferous forest account for more than 25% of the global forested area, contain more than 35% of terrestrial carbon, and harbor significant forest biodiversity (Moen et al., 2014). Hence, management of coniferous forests should integrate both, the socioeconomic needs of human communities and biodiversity conservation (Moen et al., 2014). Coniferous forests are naturally prone to large-scale stand-replacing disturbances, such as high-severity wildfires, insect outbreaks, and windstorms (Kurz et al., 2008; Seidl et al., 2014). In Eurasia, the major insect pest is the spruce bark beetle *Ips typographus* (Linnaeus, 1758). Between

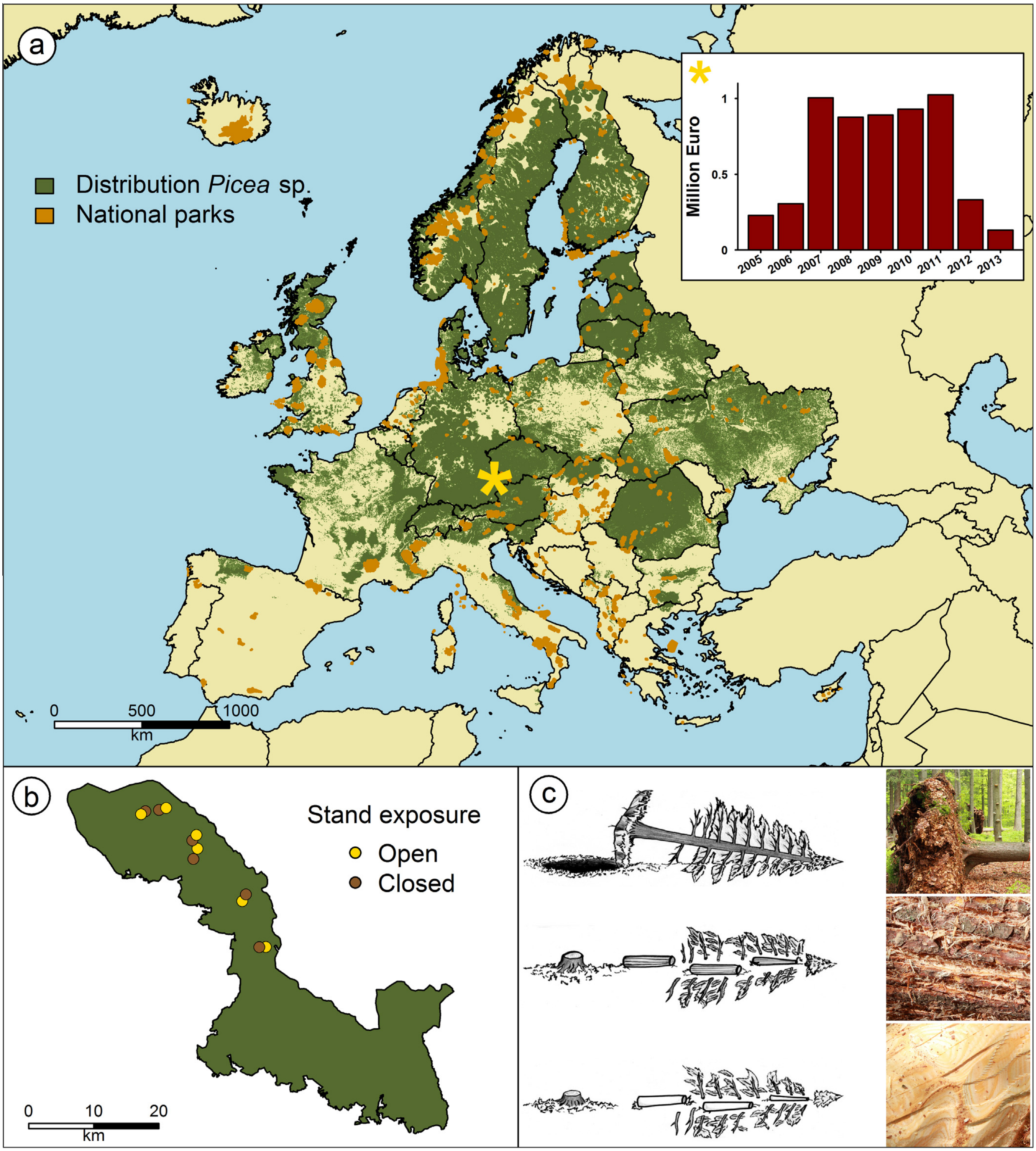

Fig. 1. (a) Recent distribution of spruce (*Picea* spp.) in Europe (based on Brus et al. (2011)). Asterisk: location of the study area, the Bavarian Forest National Park. Inset: economic costs of debarking in the Bavarian Forest National Park. (b) Location of 12 artificial windthrows within the study area; on each plot, three mature spruce trees were felled. (c) Three felled mature spruces on each plot: top row, uprooted and uncut tree (control), middle row, cut tree with scratched bark, and bottom row, cut tree completely debarked.

1950 and 2000, windstorms and outbreaks of *I. typographus* have damaged 18.7 million m^3 and 2.9 million m^3 wood volume annually in Europe (Schelhaas et al., 2003).

Not surprisingly, bark beetle eruptions have intensified discussions of how to restore economic values following disturbances, e.g., through salvage logging, and how to decrease population densities of bark beetles to avoid further spread of these insects (Black, 2005; Lindenmayer et al., 2008; Stokstad, 2006). As a consequence, forest management has developed a "search-and-destroy" tradition, in which infested trees are either removed or treated on-site to become unsuitable as breeding habitat of insect pests (Fettig et al., 2007; Nikiforuk, 2011).

Early successional stages of coniferous dead-wood harbor the majority of saproxylic biodiversity (Beudert et al., 2015; Bouget and Duelli, 2004; Lindhe et al., 2005; Saint-Germain et al., 2007) and can determine the occurrence of endangered saproxylic beetle species of later successional decay stages (Weslien et al., 2011). Hence, mechanical bark treatments, particularly debarking of disturbance affected trees, have been widely promoted as an on-site method of pest control that account for conservation targets because woody biomass is retained (Wermelinger, 2004). Despite major scientific efforts to increase the efficiency of bark beetle reduction techniques (see Wermelinger, 2004; Fettig et al., 2007; Kausrud et al., 2011, and references therein), potential collateral damage of debarking to non-target biodiversity of early decay stages has been largely ignored. Nevertheless, debarking of storm-felled spruce is currently applied, particularly in conventionally managed forests (e.g., in remote mountains, where timber of low economic value is treated on-site to avoid pest outbreaks) and in protected areas, which are legally mandated to reduce insect pests (Connor and Wilkinson, 1983; Haack and Petrice, 2009; Juha and Turcani, 2008; Thorn et al., 2015a, 2014). In many protected areas where debarking must occur, the costs can run into millions of Euros per year (Fig. 1). Hence, a sustainable pest management should combine an efficient reduction of *I. typographus* at low collateral damage to biodiversity while keeping economic costs low.

We created artificial windthrows to compare two mechanical bark treatments – debarking and bark-scratching – against an untreated control tree. We investigated species densities of three species groups (wood-inhabiting fungi, saproxylic beetles and parasitoid wasps), as well as the number of wood wasp emergence holes and holes made by foraging woodpeckers to quantify potential collateral damage of mechanical bark treatments. Furthermore, we recorded the amount of time needed to complete bark treatments to estimate the economic costs of debarking and bark-scratching. For this time-study, we used a bark-scratching device (mounted on a conventional chainsaw) and a light-weighted chainsaw itself for bark-scratching.

2. Material and methods

2.1. Study area and experimental design

The study was conducted in the Bavarian Forest National Park in southeastern Germany (Fig. 1a). Forest stands in this area are naturally dominated by Norway spruce (*Picea abies*). These forests have experienced two extensive waves of *I. typographus* outbreaks during the last 20 years and a major windstorm in 2007, which affected more than 2000 ha of mature spruce stands (Müller et al., 2008; Thorn et al., 2014).

We distributed twelve artificial windthrows across the northern part of the Bavarian Forest National Park. Sun-exposure can be of higher importance to saproxylic beetles than substrate characteristics such as diameter or host tree species (Lindhe et al., 2005). To control for such effects of stand exposure, we established six plots in stands with high canopy closure and hence, shady conditions. Six additional plots were established at sunny forest edges without canopy cover, i.e., in salvage-logged stands or small forest gaps, resulting in six pairs of plots with a minimum distance of 200 m between each pair of open- and closed stand plot (Fig. 1b). On each plot, natural storm disturbances, i.e., windthrows, were simulated by pulling down and uprooting three mature spruce trees with steel cables and winches in April 2013 (e.g., Eriksson et al., 2008). One uprooted tree on each plot was left as a control. The other two trees per plot were cut off the root plates, and branches were cut off and left on the ground to prepare mechanical bark treatments.

2.2. Mechanical bark treatments and economic costs

Debarking of experimental trees was executed by debarking devices mounted on conventional chainsaws and bark-scratching by bark-scratching devices mounted on conventional chainsaws and light weighted chainsaws itself (Fig. S1). Bark-scratching consisted of regular scratches that disrupt phloem approximately every 3 cm, whereas debarking removed all phloem. All trees had similar physical attributes. Mean heights and standard deviations of control trees were 24.7 ± 3.7 m, scratched trees = 20.2 ± 3.7 m and debarked trees = 19.9 ± 4.1 m. Mean diameter at breast height (1.3 m) of control trees was 0.43 ± 0.1 m, and 0.39 ± 0.1 m for scratched and debarked trees. Treatments were completed two days after experimental felling and thus before colonization by *I. typographus*.

We recorded the amount of time needed to complete the processes of mechanical bark treatments following a standard debarking procedure for storm-felled trees. Time measurements started with cutting off the root plate and ended when bark treatments where completed. This time study was carried out on 15 separate trees per treatment (debarking device, bark-scratching device, bark-scratching by chainsaw), resulting in 45 additional experimental trees independent of the main experimental design. Following treatments, the time needed for bark treatments was standardized by tree volume and used as a surrogate for economic cost in subsequent analysis.

2.3. Biodiversity surveys

We sampled emerging assemblages of saproxylic beetles and parasitoid wasps on twelve artificial windthrows from June 2013 until September 2013 and from April 2014 until September 2014. We mounted stem emergence traps on each tree trunk and changed the trap position in the second season, to avoid possible sampling biases of surface covering by first-year trap position. Emergence traps were filled with 90% ethanol to preserve species material for barcoding (Brin et al., 2011; Wikars et al., 2005). All trapped saproxylic beetles were identified to the species level according to Freude et al. (1963–1984). To identify cryptic parasitoid wasps, one leg of each specimen was sent to the Canadian Centre for DNA Barcoding (CCDB) for sequence analysis. A 658 bp region near the 5′-terminus of the mitochondrial gene encoding cytochrome *c* oxidase, which includes the DNA barcode region for the animal kingdom (Hebert et al., 2003), was amplified by PCR and sequenced using standardized high-throughput protocols (Ivanova et al., 2006).

Fruiting bodies of wood-inhabiting fungi were assessed visually on the complete trunk surface in October 2014 and April 2015. Abundance was estimated according to bark surface covered by fruiting bodies in three classes (<1%, 1–10%, >10%) and species were identified either in the field or, especially for cryptic species of corticoid-like fungi, in the laboratory (Eriksson and Ryvarden, 1987; Knudsen and Vesterhold, 2008; Ryvarden and Gilbertson, 1993). Wood wasp emergence holes, and holes made by foraging woodpeckers feeding on insect larvae were counted on the complete trunk surface in May 2015.

2.4. Data analysis

Prior to statistical analysis, biodiversity data were aggregated for each species group to the trunk level, representing species densities (sensu Gotelli and Colwell (2001)) of 36 experimentally felled trees. All statistical analyses were completed using the statistical software R 3.2.0 (www.r-project.org). We applied Quasi-Poisson linear models to test the effect of debarking and bark-scratching to species densities of all species and red-listed saproxylic beetle species (according to the Red-list of Bavaria, www.lfu.bayern.de), abundances of *I. typographus*, number of wood wasp emergence holes, number of holes made by foraging woodpeckers, and the costs (time) for debarking and bark-scratching. Stand exposure (open stand, closed stand) was included as a factorial co-variable for biodiversity modelling. We used simultaneous inference procedures with adjustment of p-values for multiple testing by means of the function "glht" to compare mechanical bark treatments among each others (R package "multcomp"; Hothorn et al., 2008). We used non-metric multidimensional scaling and distance-based analysis of similarity (ANOSIM) to visualize and test differences within species assemblage composition among the different bark treatments (Clarke, 1993). The obtained p-values were adjusted according to Benjamini and Hochberg (1995). Similarity percentages were calculated to identify most discriminating species of wood-inhabiting fungi and saproxylic beetles between bark treatments (Clarke, 1993).

3. Results

Debarking and bark-scratching significantly decreased the median number of emerging *I. typographus* beetles to 4% (debarked) and 11% (bark-scratched) of the number of individuals emerging from untreated control trees (Fig. 2). The expenditure of time needed for scratching by bark-scratching device was significantly lower (20%) than debarking, whereas bark-scratching by chainsaw needed a similar amount of time as conventional debarking (Fig. 3).

In total, we recorded 39 species of wood-inhabiting fungi and 26,586 individual saproxylic beetles, including *I. typographus* (1920 individuals), belonging to 122 species (Table S2). We captured 335 individual parasitoid wasps, representing 84 species (Table S2) or, if identification to species level was not feasible, of molecular operational taxonomic units (MOTUs) that are represented by BINs (Barcode Index Number) that closely approximate species (Ratnasingham and Hebert, 2013). Compared to control trees, debarking of felled trees significantly reduced the species density of wood-inhabiting fungi, saproxylic beetles, red-listed saproxylic beetles and parasitoid wasps. By contrast, bark-scratching did not reduce the overall species density of wood-inhabiting fungi, saproxylic beetles, parasitoid wasps or species densities of red-listed saproxylic beetles species (Fig. 4). Nevertheless, the abundance of wood wasp emergence holes and holes made by foraging woodpeckers was reduced by both debarking and bark-scratching (Fig. 4). Species densities of wood-inhabiting fungi was higher in open stands and species densities of red-listed saproxylic beetle species was higher in closed stands, whereas stand exposure had no effects on remaining target variables (Table S1 for statistical details). We detected 584 wood wasp emergence holes on control trees, 84 on bark-scratched trees, and zero on debarked trees. We detected 685 holes made by foraging woodpeckers on control trees, 50 on bark-scratched trees, and zero on debarked trees (Fig. 4).

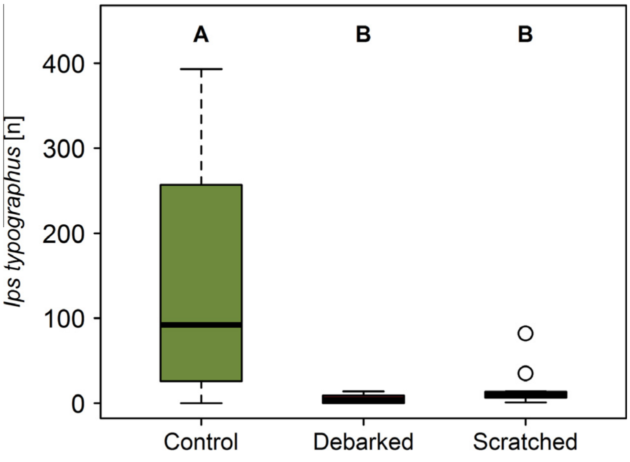

Fig. 2. Abundance of emerging *Ips typographus* caught in stem emergence traps on control trees, debarked trees, and trees with bark-scratching in artificial windthrows. Significances indicated by upper case letters and based on Quasi-Poisson linear models corrected for stand exposure (see Table S1 for statistical details).

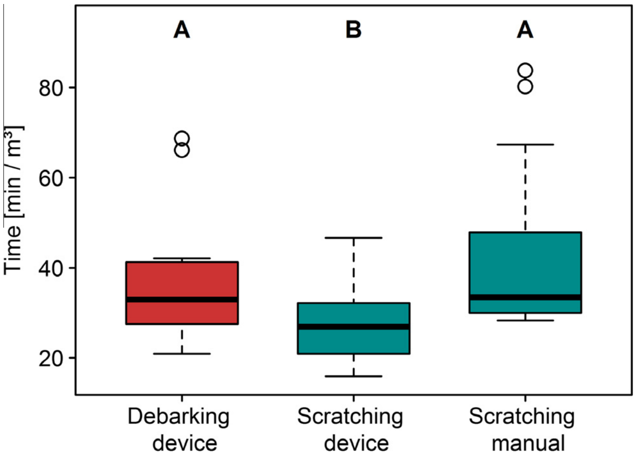

Fig. 3. Time per cubic meter of wood needed to mechanically debark felled trees, scratch the bark of felled trees by a bark-scratching device, or by a lightweight chainsaw. Significances indicated by upper case letters and based on Quasi-Poisson linear models (see Table S1 for statistical details).

ANOSIM revealed that assemblages of wood-inhabiting fungi differed significantly ($p = 0.03$) in pairwise comparisons of all three treatments (Fig. 5a). The assemblages of saproxylic beetles differed significantly between control trees and debarked trees ($p = 0.03$), almost significantly between bark-scratched trees and debarked trees ($p = 0.06$), but not between control trees and bark-scratched trees ($p = 0.18$; Fig. 5b). Parasitoid wasps revealed distinct assemblages between bark-scratched trees and debarked trees ($p = 0.03$) as well as between debarked and control trees ($p = 0.03$) but not between control trees and bark-scratched trees ($p = 0.81$; Fig. 5c).

Dissimilarities in assemblages of wood-inhabiting fungi between control and bark-scratched trees were predominantly characterized by *Phlebiopsis gigantea*, *Gloeophyllum sepiarium*, and *Exidia pithya* (54%). Dissimilarities between control and debarked trees were characterized by *E. pithya*, *Stereum sanguinolentum* and *G. sepiarium* (46%) and between bark-scratched trees and debarked trees by *P. gigantea*, *G. sepiarium*, and *Schizophyllum commune* (53%). Dissimilarities in assemblages of saproxylic beetles were discriminated by *Trypodendron lineatum*, *I. typographus*, and *Crypturgus pusillus*, which contributed 54% to dissimilarities between control and bark-scratched trees and 64% to

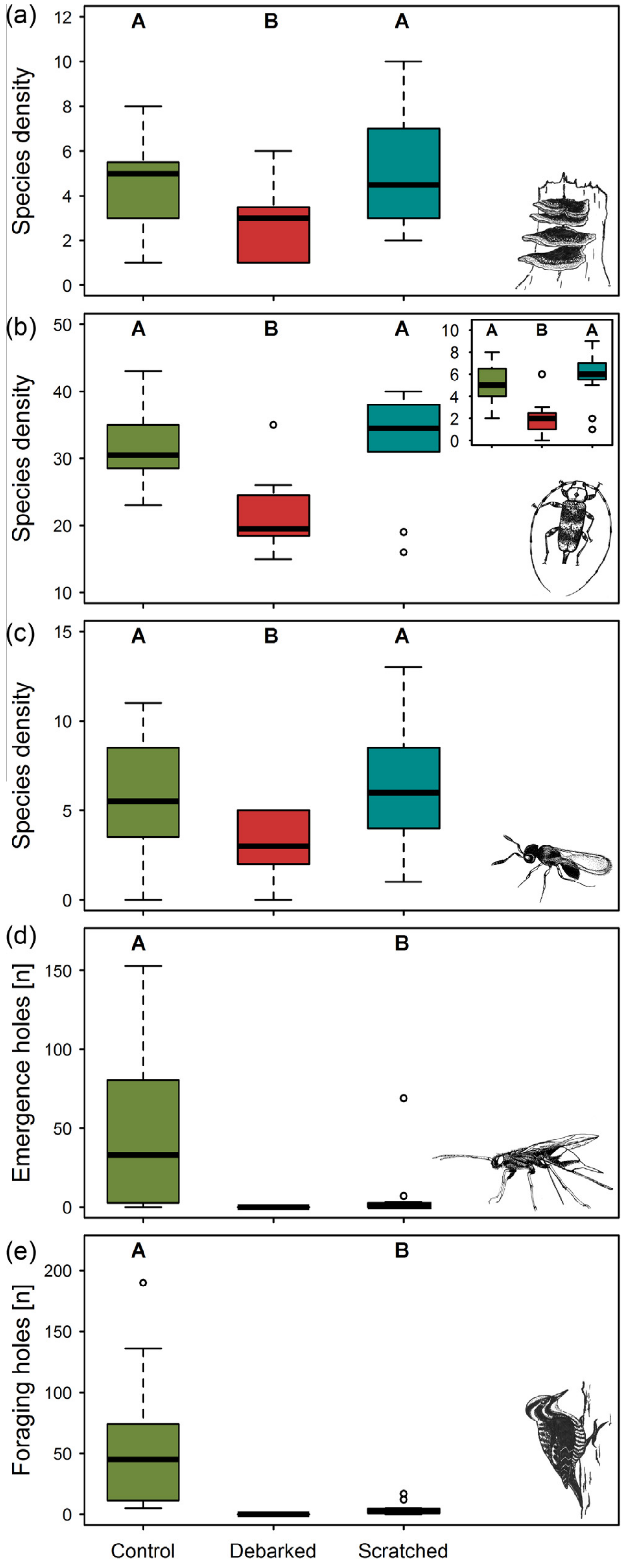

Fig. 4. (a) Species density of wood-inhabiting fungi, (b) species density of saproxylic beetles (including *I. typographus*), (c) species density of parasitoid wasps, (d) number of wood wasp emergence holes, and (e) number of holes made by woodpeckers. Significances indicated by upper case letters and based on Quasi-Poisson linear models corrected for stand exposure (note that simultaneous test were not meaningful if zero holes were recorded on debarked trees, see Table S1 for statistical details).

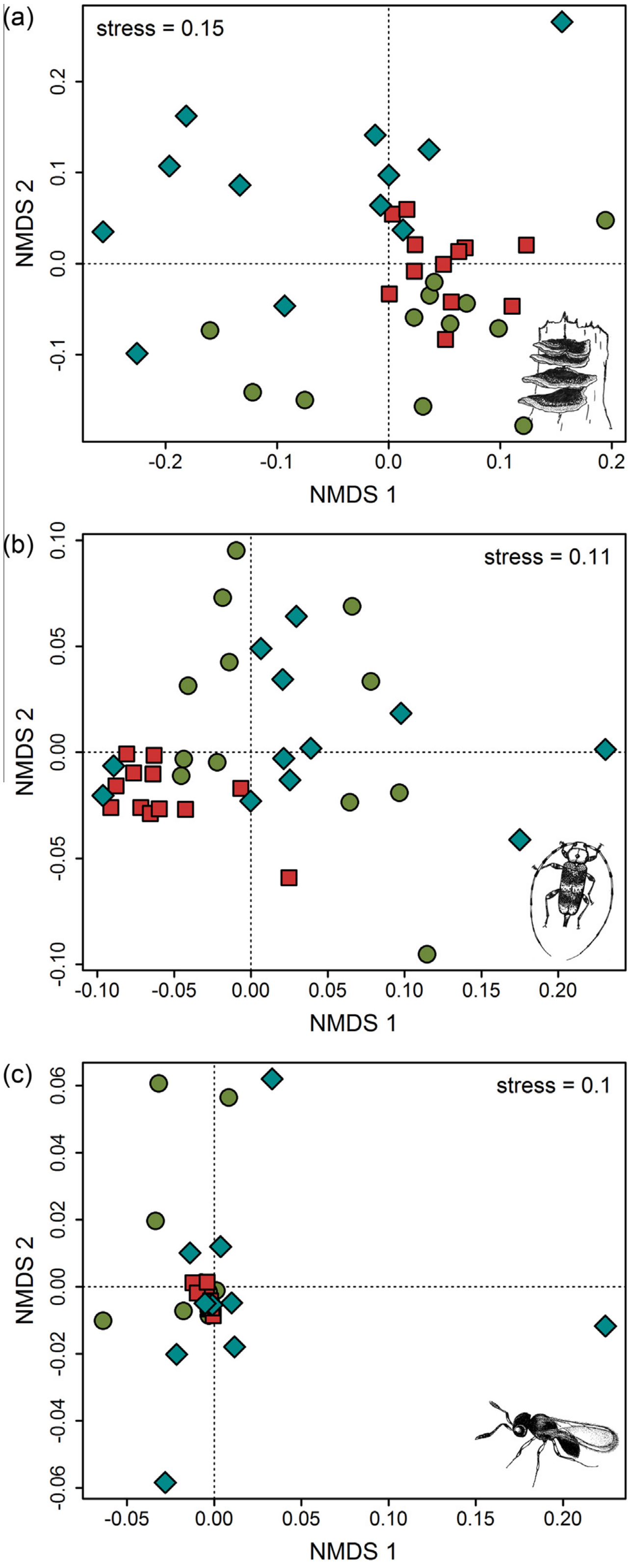

Fig. 5. Non-metric multidimensional scaling of species assemblages of (a) wood-inhabiting fungi, (b) saproxylic beetles (including *I. typographus*), and (c) parasitoid wasps in debarked felled spruce trees (red squares), bark-scratched trees (blue diamonds) and control trees (green circles).

dissimilarities between control and debarked trees. *T. lineatum*, *Epuraea deubeli*, and *Dryocoetes autographus* discriminated 55% of dissimilarities between bark-scratched trees and debarked trees (see Table S2 for species abundances).

4. Discussion

Debarking of storm-felled trees has been widely promoted throughout Eurasia as an on-site method of pest control that accounts for conservation targets because wood biomass is retained. Our results demonstrated that debarking of storm-felled trees reduces not only the abundance of the target insect pest *I. typographus*, but also reduces species density of non-target taxa. This outcome undermines conservation aims of most protected areas where debarking is applied. However, bark-scratching, as an alternative to debarking, proved to be successful both in substantially lowering the abundance of *I. typographus* and in preserving most of the non-target saproxylic biodiversity, and this was achieved at lower economic costs. However, bark-scratching did have some negative effects in common with debarking, such as altered structure of assemblages of wood-inhabiting fungi, the significant reduction in the abundance of wood wasp emergence holes and reduced numbers of holes made by foraging woodpeckers. Therefore, bark-scratching of downed trees, like debarking, might affect higher trophic levels of biodiversity (e.g., impaired food availability for woodpeckers) and should be applied only if pest management is urgently needed.

4.1. Efficiency of pest control and collateral damage

Our study confirmed that debarking reduces the number of emerging *I. typographus* to 4% of that of an untreated control tree (Kausrud et al., 2011; Wermelinger, 2004). Additionally, we have demonstrated the effectiveness of bark-scratching in reducing the number of emerging *I. typographus* (11% of that of a control tree). The lack of *I. typographus* colonization of debarked trees was as expected, but bark-scratched trees still retain significant portions of bark and phloem, which theoretically allow breeding of *I. typographus*. One explanation why *I. typographus* did not successfully breed in bark-scratched trees, could be the difficulty or inability of bark beetle larvae to cross areas lacking bark (De Jong and Grijpma, 1986).

Despite the slightly more effective reduction of *I. typographus* by debarking (Fig. 2) compared to bark-scratching, both methods of bark treatment significantly revealed an approximately 90% pest-reducing effect at the scale of a single tree. This is similar to the pest-reducing effect of post-storm logging at the stand scale found in a study using flight-interception traps (Thorn et al., 2014). Hence, our results legitimize debarking as well as bark-scratching to decrease population densities of *I. typographus* as valuable alternatives to conventional post-storm logging (Eriksson et al., 2006; Schroeder, 2010). However, debarking resulted in a reduction in the species densities of saproxylic beetles, wood-inhabiting fungi, and parasitoid wasps to levels approximately 2/3 of that of a control tree. This finding at the scale of a single tree is likewise similar to the collateral damage of post-storm logging at the stand scale, which reduced species densities of saproxylic beetles also to 2/3 of that of an unlogged control (Thorn et al., 2014). Beside the direct mechanical removal of phloem as habitat for saproxylic beetles, an extensive loss may be also caused by collateral damage among commensals and predators of *I. typographus* (Schroeder, 2007; Weslien, 1992). For instance, the genus *Roptrocerus* of parasitoid wasps was most abundant in bark-scratched and control trees, reflecting the loss of large host bark beetles such as *I. typographus* or *T. lineatum* in debarked trees (Wermelinger, 2002). Furthermore, a number of wood-inhabiting fungi may disappear in the absence of their arthropod spore vectors, and vice versa a number of beetles may disappear in absence of their fungal hosts (Jonsell et al., 2013; Müller et al., 2002; Strid et al., 2014; Thorn et al., 2015b).

Bark-scratched trees still provide a considerable amount of phloem, promoting the diversity of saproxylic insects. Hence, bark-scratching achieved levels of biodiversity similar to those of control trees. Additional species might be related to the high abundance of *T. lineatum* that colonize Norway spruce in successional stages similar to those colonized by *I. typographus*, but that do not feed on phloem and instead bore deep holes to the heart wood (Wermelinger et al., 2002). *T. lineatum* is closely associated with wood-decaying fungi and other species of bark beetles and hence might promote high levels of biodiversity in bark-scratched trees (Müller et al., 2002).

4.2. Implications for pest management

Increasing frequency and extent of natural disturbances, will increasingly challenge managers and policy makers of both conventional production forests and protected areas (Kurz et al., 2008). A major challenge will be to balance pest management after large scale storm events with preservation of high levels of biodiversity in early successional stages (Saint-Germain et al., 2007). The combination of insect outbreaks and windstorms is predicted to damage 60 million m^3 of wood between 2021 and 2030 in Europe (Seidl et al., 2014). The results of this investigation suggest that conventional pest management by debarking will cause both a reduction of biodiversity and major economic costs in the near future. We therefore urge responsible authorities to revise the guidelines dealing with disturbance affected spruce forest in the Palearctic region. If policy makers demand pest management, bark-scratching should replace debarking to maintain high levels of biodiversity, even in conventionally managed forests. This is because it achieves the best compromise between pest reduction and achievement of conservation goals at lower economic costs. However, bark-treatment devices should be optimized in future.

Assemblages of wood-inhabiting fungi differed significantly between bark-scratched trees and control trees, and holes made by foraging woodpeckers and wood wasp emergence holes were predominantly found in control trees (Fig. 4), indicating that bark-scratching had some negative effects in common with debarking. Hence, our findings suggest setting aside disturbance-affected spruce trees to maintain high levels of saproxylic biodiversity. Natural resource managers should carefully evaluate whether costs for pest management could be reduced by applying a benign-neglect (e.g., allowing natural disturbances without human intervention) strategy toward storm-felled trees.

Outbreaks of *I. typographus* are commonly triggered by large scale storms up to tens of thousands of hectares (Stadelmann et al., 2013). The effectiveness and feasibility of bark-scratching (as well as debarking) to avoid pest outbreaks will depend on the total volume of affected timber, the timing of a storm, the colonization process of *I. typographus* corresponding to the timing of a storm, and the budget available for treatments. Given the relatively short time span in which mechanical bark treatment might be effective, bark-scratching may not be feasible in extensive and completely storm-felled stands up to several 100 ha. However, the majority of storm-felled trees naturally occur in scattered patches, which can be treated completely prior to an infestation.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.foreco.2015.12.044.

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